

Longitudinally Polarized Photoproduction of Heavy Flavors at Next-to-Leading Order of QCD

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Abstract. We present a phenomenological study of charm quark photoproduction in longitudinally polarized lepton-hadron collisions at next-to-leading order accuracy of QCD. Our results are based on a recently developed, flexible parton-level Monte Carlo program for spin-dependent heavy flavor hadroproduction, which we extend to deal also with both direct and resolved photon contributions. The subsequent hadronization into charmed mesons is modeled in our calculations, which allows us to compare with data on double-spin asymmetries for D^0 meson production taken by the COMPASS collaboration. In general, next-to-leading order QCD corrections are found to be very significant and do not cancel in spin asymmetries. We elucidate the role of the individual hard scattering subprocesses and determine the range of parton momentum fractions predominantly probed for charm production at COMPASS. Theoretical uncertainties are estimated by varying renormalization and factorization scales and parameters controlling the hadronization of the charm quarks.

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1 Motivation and Introduction

The quest to understand the partonic structure of the nucleon spin remains to be one of the key research areas in Hadronic Physics even after more than 25 years of strenuous experimental and theoretical efforts. In particular, the polarized gluon density, defined as

$$\Delta g(x, \mu) \equiv g_+(x, \mu) - g_-(x, \mu), \quad (1)$$

is still one of the most elusive quantities associated with the non-perturbative partonic structure of hadrons. Here, g_+ (g_-) denotes the probability of finding a gluon at a scale μ with light-cone momentum fraction x and helicity $+$ ($-$) in a proton with helicity $+$. The total, x integrated gluon polarization,

$$\Delta g(\mu) \equiv \int_0^1 \Delta g(x, \mu) dx, \quad (2)$$

and a similar contribution from the sum of all quarks and antiquarks, enters the helicity sum rule of the nucleon along with the orbital angular momenta of quarks and gluons [1]. The challenge is to precisely map $\Delta g(x, \mu)$ in a wide range of x in order to minimize extrapolation uncertainties in the first moment (2).

Currently, the best constraints on $\Delta g(x, \mu)$ are derived from global QCD analyses [2,3] which treat all available experimental probes simultaneously and consistently at a given order in the strong coupling α_s in perturbative QCD. The availability of next-to-leading order (NLO)

QCD corrections is essential for any meaningful, quantitative analysis of parton densities. In particular, single-inclusive pion [4] and jet production [5], measured in spin-dependent proton-proton collisions at BNL-RHIC [6], have started to put significant limits on the amount of gluon polarization in the nucleon [2]. New, preliminary single and di-jet data from the STAR collaboration [7] show for the first time tantalizing hints for a non-zero $\Delta g(x, \mu)$ [8,9]. Due to the given kinematics, the current probes mainly constrain Δg in the medium-to-large x region, $0.05 \lesssim x \lesssim 0.2$, which is not sufficient to reliably determine its integral (2). A very significant contribution of up to one unit of \hbar , i.e., twice the proton spin, can still come from the unexplored small x region [2]. Narrowing down the uncertainties on $\Delta g(x, \mu)$ and, at the same time, extending the range in x continues to be the main objective of experimental efforts in the years to come. Eventually, only a future high-energy polarized electron-proton collider, such as the EIC project [10], will finally be able to quantitatively address all the remaining open questions related to the helicity structure in the small x region [11].

World-data on polarized inclusive and semi-inclusive deep-inelastic scattering are pivotal in constraining the helicity quark and antiquark densities [2,3,8], but due to lack of sufficient kinematic coverage of present fixed-target experiments, information on the gluon density is notoriously difficult to obtain from QCD scaling violations. Viable probes of $\Delta g(x, \mu)$ at fixed-target energies comprise of one- and two-hadron and open charm production

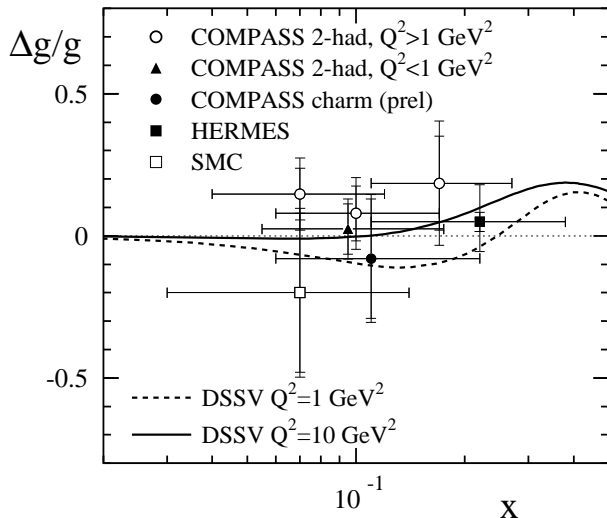


Fig. 1. Approximate LO extractions of $\Delta g/g$ from polarized lepton-nucleon scattering experiments [12, 13, 14, 15] compared to results of the DSSV global analysis of helicity PDFs [2] based on RHIC pp data for two different scales Q .

and have been exploited by several experimental collaborations [12, 13, 14, 15]. The proper theoretical description of these processes depends on the virtuality of the probing photon and is in general more involved than corresponding calculations for hadron-hadron scattering. In case of photoproduction, where a quasi-real photon is exchanged, one has to include also “resolved” contributions, where the photon fluctuates into a vector meson of the same quantum numbers before the hard scattering with partons in the proton takes place. If the virtuality Q of the photon is of $\mathcal{O}(1 \text{ GeV})$ or higher, resolved processes are sufficiently suppressed but the additional momentum scale Q greatly complicates the calculations of phase-space and loop integrals.

Not surprisingly, only very few calculations at NLO of QCD are available in case of polarized beams and targets [16, 17, 18], none of which for large virtualities Q . As a consequence, the available data sets on hadron and open charm production [12, 13, 14, 15] have not been included in global QCD analyses of helicity parton densities so far. Experiments have analyzed their data only in terms of the gluon polarization, $\Delta g(x, \mu)/g(x, \mu)$, under certain simplifying assumptions and based on leading order (LO) matrix elements. Nonetheless, the results of these exercises, illustrated in Fig. 1, are in fairly good agreement with a NLO extraction of $\Delta g(x, \mu)$ including the RHIC pp data [2]. While determinations of Δg at fixed-target energies are more involved and provide less of a constraint than collider data, they are crucial for further testing and establishing the assumed universality of helicity-dependent parton densities and hence for our understanding of the spin structure of the nucleon and QCD in general. On the one hand, lepton-nucleon scattering experiments are sensitive to different partonic hard scattering processes than

jet or hadron production at RHIC and, on the other hand, the relevant momentum fractions x fall within the range already probed by pp data.

In this paper, we present a comprehensive phenomenological analysis of longitudinally polarized photoproduction of heavy flavors at NLO of QCD. To this end, we extend our recently developed flexible parton-level Monte Carlo program for spin-dependent heavy flavor hadroproduction [19] by including all relevant subprocesses for direct [16, 17] and resolved [19, 20] photon contributions. To facilitate the comparison to data, the hadronization of the produced charm quarks into charmed mesons and, as an additional option, their semi-leptonic decays can be modeled in our calculations based on the phenomenological functions used in Ref. [21]. The presented results will allow one to consistently include available and upcoming data on spin-dependent open charm photoproduction into future global QCD analyses of helicity parton densities at NLO accuracy.

As a first application, we examine in detail all aspects of open charm production in the kinematic regime accessible with the COMPASS experiment [15]. We will demonstrate that NLO corrections are very significant and do not cancel in double-spin asymmetries used to extract information on the polarized gluon density $\Delta g(x, \mu)$. We elucidate the relevance of the individual direct and resolved partonic subprocesses and estimate theoretical uncertainties by varying renormalization and factorization scales and parameters controlling the hadronization of the produced charm quarks into experimentally observed D mesons. Finally, we shall illustrate the sensitivity of the existing data on the double-spin asymmetry for charm quark photoproduction [15, 22, 23, 24] to $\Delta g(x, \mu)$ and compare our estimates of the relevant range of momentum fractions x with those obtained by the COMPASS collaboration.

We note that our flexible Monte Carlo code is capable of computing any infrared safe heavy flavor photoproduction cross section at $\mathcal{O}(\alpha_s^2)$ in longitudinally polarized lepton-nucleon collisions, including correlations of the produced heavy quark pair. Our results complement and significantly extend previously existing spin-dependent NLO calculations of single-inclusive heavy quark yields based on largely analytical methods [16, 17], where the resolved contribution was neglected, any information on the partonic recoil system was lost, and most experimental cuts could not be implemented. The results presented here will be also useful for future studies of spin-dependent charm photoproduction at an EIC [10].

The outline of the paper is as follows: in Sec. II we briefly review some of the technical aspects of setting up a parton-level Monte Carlo program for heavy flavor photoproduction in polarized lepton-nucleon collisions at NLO accuracy. In Sec. III we present a detailed phenomenological study of open charm quark production at COMPASS, including the relevance of NLO corrections, the role of the different hard scattering subprocesses, an estimate of the relevant momentum fractions x , and an assessment of theoretical uncertainties. We summarize our results in Sec. IV.

2 Technical Framework

We consider heavy quark photoproduction in longitudinally polarized lepton-nucleon collisions at NLO accuracy of QCD by consistently including for the first time both direct and resolved photon contributions. In order to compute arbitrary infrared-safe observables within flexible experimental acceptance cuts and to account for the hadronization of the produced heavy quark pair, all phase-space integrations are performed numerically with appropriate Monte Carlo techniques. To this end, we follow closely the subtraction method devised and used in Refs. [25, 26]. In the following, we will only briefly outline the technical details relevant for the case of polarized photoproduction.

Assuming, as usual, factorization, the inclusive cross section for producing a heavy quark Q in spin-dependent lepton-proton collisions at a center-of-mass system (c.m.s.) energy \sqrt{S} can be written as a convolution,

$$\begin{aligned} d\Delta\sigma^Q &\equiv \frac{1}{2} \left[d\sigma_{++}^Q - d\sigma_{+-}^Q \right] \\ &= \sum_{a,b} \int dx_a dx_b \Delta f_{a,l}^l(x_a, \mu_f) \Delta f_{b,p}^p(x_b, \mu_f) \mathcal{S} \\ &\quad \times d\Delta\hat{\sigma}_{ab}(x_a, x_b, S, m_Q, k_1, k_2, \mu_f, \mu_r), \end{aligned} \quad (3)$$

where the subscripts \pm in (3) label the helicity states of the lepton and proton. In analogy to Eq. (1), the $\Delta f_{a,b}^{l,p}$ denote the spin-dependent parton distribution functions (PDFs) of flavor a, b in a lepton l or proton p . The sum in (3) is over all contributing partonic processes $ab \rightarrow Q\bar{Q}c$, including those with a direct photon, i.e., $a = \gamma$, with $d\Delta\hat{\sigma}_{ab}$ the associated polarized hard scattering cross sections. The required spin-dependent matrix elements squared $\Delta|M_{ab}|^2$ at NLO accuracy in $d = 4 - 2\varepsilon$ dimensional regularization for the direct and resolved photon processes can be taken from [16] and [20], respectively. Corresponding unpolarized results can be found in Refs. [25, 26, 27]. At $\mathcal{O}(\alpha_s^2)$, parton c can be either a gluon or a light (anti-)quark producing an additional jet or hadron which is usually not observed in experiment. $k_{1,2}$ denote the four-momenta of the heavy quark Q and antiquark \bar{Q} with mass m_Q , i.e., $k_{1,2}^2 = m_Q^2$. μ_r and μ_f are the renormalization and factorization scale, respectively, which are typically chosen as a combination of the hard scales characterizing the process.

The “measurement function” \mathcal{S} in Eq. (3) defines the observable, for instance, through a set of step functions implementing the experimental cuts imposed on the final-state particles and selecting a certain bin in a kinematical distribution of interest. In case of the COMPASS experiment, single-inclusive spectra of D mesons, differential in transverse momentum p_T^D , are measured [15, 22, 23, 24]. Thus, the cross section (3) at the heavy quark-level is not yet sufficient for comparing theory with experimental results and needs to be convoluted with an additional phenomenological function $D^{Q \rightarrow H_Q}$ modeling the hadronization of the charm quark:

$$d\Delta\sigma^{H_Q} = d\Delta\sigma^Q \otimes D^{Q \rightarrow H_Q}. \quad (4)$$

We will specify our choice for $D^{Q \rightarrow H_Q}$, along with all other non-perturbative inputs, in Sec. 3. Even though not relevant for the phenomenological applications considered in this paper, our flexible Monte Carlo program can also account for the semi-leptonic decays of D mesons if needed.

For the integration of the fully exclusive partonic cross sections $d\Delta\hat{\sigma}_{ab}$ in Eq. (3), we generalize the framework used for unpolarized heavy quark production in [25, 26] to deal with singular regions of phase-space. The gist of the method is to add and subtract appropriate spin-dependent counter terms to $d\Delta\hat{\sigma}_{ab}$ which can be integrated analytically with respect to momenta of unresolved partons. For all resolved photon processes, $a \neq \gamma$, we can adopt the expressions obtained in our recent calculation of polarized heavy quark hadroproduction at $\mathcal{O}(\alpha_s^3)$ [19], since these processes share the same hard scattering matrix elements. Hence, we only need to consider processes with a direct photon, $d\Delta\hat{\sigma}_{\gamma b}$, in the following.

In general, for a numerically efficient implementation of the subtraction method it is convenient [25, 26, 19] to express the three-body phase-space in terms of variables where soft and collinear singularities are particularly transparent. This is achieved by choosing $x = (k_1 + k_2)^2/s$, the invariant mass of the $Q\bar{Q}$ pair scaled by the available partonic c.m.s. energy squared, i.e., $4m_Q^2/s \leq x \leq 1$. In addition, one uses $-1 \leq y \leq 1$, the cosine of the angle between the z -direction, aligned with the spatial direction of parton a , and \mathbf{k}_3 , the momentum of parton c , in the c.m.s. of the incoming partons. Soft and collinear regions of phase-space are then simply associated with $x = 1$ and $y = \pm 1$, respectively, and the hard scattering matrix element for the process $\gamma b \rightarrow Q\bar{Q}c$ can be written as

$$\Delta|M_{\gamma b}|^2 = \frac{\Delta f_{\gamma b}(s, m_Q, x, y, \theta_1, \theta_2)}{s^2(1-x)^2(1-y^2)}, \quad (5)$$

where $\Delta f_{\gamma b}$ is regular for $x = 1$ and $y = \pm 1$. The angles $\theta_{1,2}$ are used to parametrize the spatial orientation of $k_{1,2}$ with respect to the plane span by the other three momenta in the c.m.s. of the $Q\bar{Q}$ pair; for further details, see [25, 26, 19]. We note that the genuine NLO subprocess $\gamma q(\bar{q}) \rightarrow Q\bar{Q}q(\bar{q})$ can have only collinear singularities at $\mathcal{O}(\alpha_s^2)$.

The partonic subprocesses contributing to the direct photon cross section at $\mathcal{O}(\alpha_s^2)$, $\gamma g \rightarrow Q\bar{Q}g$ and $\gamma q(\bar{q}) \rightarrow Q\bar{Q}q(\bar{q})$, can be decomposed as [26]

$$\begin{aligned} d\Delta\hat{\sigma}_{\gamma b} &= d\Delta\hat{\sigma}_{\gamma b}^{(b)} + d\Delta\hat{\sigma}_{\gamma b}^{(c+)} + d\Delta\hat{\sigma}_{\gamma b}^{(c-)} \\ &\quad + d\Delta\hat{\sigma}_{\gamma b}^{(s)} + d\Delta\hat{\sigma}_{\gamma b}^{(v)} + d\Delta\hat{\sigma}_{\gamma b}^{(f)}. \end{aligned} \quad (6)$$

Here, $d\Delta\hat{\sigma}_{\gamma b}^{(b)}$ and $d\Delta\hat{\sigma}_{\gamma b}^{(v)}$ denote the $\mathcal{O}(\alpha_s)$ Born contribution and the $\mathcal{O}(\alpha_s^2)$ one-loop corrections to the $\gamma g \rightarrow Q\bar{Q}$ process, respectively. Analytic expressions for the virtual contributions in d dimensions, with ultraviolet divergences being subtracted at the renormalization scale μ_r , can be found in Ref. [16].

In Eq. (6), $d\Delta\hat{\sigma}_{\gamma b}^{(s)}$ denotes the soft gluon emission part of the γg scattering cross section, which can be obtained from the full d -dimensional matrix elements squared in the limit $x \rightarrow 1$ where the phase-space integrations can

be performed analytically [26]. We obtain the same result for the squared three-body amplitude in the soft limit as given in Eq. (A.14) of Ref. [26] but with the Born contribution for $\gamma g \rightarrow Q\bar{Q}$ being replaced by its spin-dependent, color-averaged counterpart, which reads in $d = 4 - 2\varepsilon$ dimensions:

$$\Delta|M_{\gamma g}|^2 = \frac{1}{2s}(4\pi\alpha_s)e^2e_Q^2\Delta B_{\gamma g} \quad (7)$$

where

$$\Delta B_{\gamma g} = \left(\frac{t_1}{u_1} + \frac{u_1}{t_1}\right) \left(\frac{2m_Q^2 s}{t_1 u_1} - 1\right). \quad (8)$$

Here, t_1 and u_1 are the usual tree-level Mandelstam variables. Contrary to the unpolarized case, $\Delta B_{\gamma g}$ receives no $\mathcal{O}(\varepsilon)$ contributions [16]. e_Q is the electromagnetic charge of the heavy quark Q in units of the coupling e , i.e., $e_c = 2/3$, and $e^2/4\pi = \alpha$.

All $2 \rightarrow 3$ processes exhibit singularities related to collinear splittings off the incoming photon ($y \rightarrow +1$) and parton b ($y \rightarrow -1$) which need to be factorized into the bare photon and proton PDFs at a scale μ_f , respectively. As for the soft contributions discussed above, the kinematics collapses to the much simpler case of $2 \rightarrow 2$ scattering, such that compact analytical expressions, summarized by $d\Delta\hat{\sigma}_{\gamma b}^{(c\pm)}$ in Eq. (6), can be obtained:

$$\begin{aligned} d\Delta\hat{\sigma}_{\gamma b}^{(c\pm)} &= -(4\pi)^{\varepsilon-2}\Gamma[1+\varepsilon]\left(\frac{2}{\omega}\right)^{\varepsilon}\frac{s^{-1-\varepsilon}}{4\varepsilon}d\text{PS}_2 \\ &\times \left[\left(\frac{1}{1-x}\right)_{\bar{\rho}} - 2\varepsilon\left(\frac{\log(1-x)}{1-x}\right)_{\bar{\rho}}\right] \\ &\times \Delta f_{\gamma b}^{(c\pm)}(s, m_Q, x, \theta_1), \end{aligned} \quad (9)$$

where

$$\Delta f_{\gamma g}^{(c+)}(x, \theta_1) = 0, \quad (10)$$

$$\begin{aligned} \Delta f_{\gamma g}^{(c-)}(x, \theta_1) &= 32\pi\alpha_s s(1-x) \\ &\times \Delta|M_{\gamma g}|^2|_{p_2 \rightarrow xp_2} \Delta P_{gq}(x), \end{aligned} \quad (11)$$

$$\begin{aligned} \Delta f_{\gamma q}^{(c+)}(x, \theta_1) &= 32\pi\alpha_e e_Q^2 s(1-x) \\ &\times \Delta|M_{q\bar{q}}|^2|_{p_1 \rightarrow xp_1} \Delta P_{q\gamma}(x), \end{aligned} \quad (12)$$

$$\begin{aligned} \Delta f_{\gamma q}^{(c-)}(x, \theta_1) &= 32\pi\alpha_s s(1-x) \\ &\times \Delta|M_{\gamma g}|^2|_{p_2 \rightarrow xp_2} \Delta P_{gq}(x). \end{aligned} \quad (13)$$

Here, p_1 and p_2 denote the momenta of the photon and parton b , respectively. Both, the standard two-body phase-space $d\text{PS}_2$ in (9) and the Born matrix elements squared in Eqs. (10)-(13) are to be evaluated with appropriate collinear kinematics as indicated by the shift of momenta $p_2 \rightarrow xp_2$, etc; further details can be found in Refs. [25, 26, 19].

The resulting $1/\varepsilon$ divergence in (9) assumes the form dictated by the factorization theorem, i.e., a convolution of d -dimensional helicity-dependent LO splitting functions $\Delta P_{ij}(x)$ and Born matrix elements $\Delta|M_{ab}|^2$. By adding

appropriate counter cross sections to (9), which to $\mathcal{O}(\alpha\alpha_s^2)$ schematically read

$$\begin{aligned} d\Delta\hat{\sigma}_{\gamma b}^{(c)}(\mu_f) &= -\frac{\alpha_s}{2\pi} \sum_i \int \frac{dx}{x} \left[\Delta\mathcal{P}_{i\gamma}(x, \mu_f) d\Delta\hat{\sigma}_{ib}^{(b)}(xs) \right. \\ &\quad \left. + \Delta\mathcal{P}_{ib}(x, \mu_f) d\Delta\hat{\sigma}_{\gamma i}^{(b)}(xs) \right], \end{aligned} \quad (14)$$

where

$$\mathcal{P}_{ij}(x, \mu_f) = \Delta P_{ij}(x) \left[-\frac{1}{\varepsilon} + \gamma_E - \ln 4\pi + \ln \frac{\mu_f^2}{\mu^2} \right] + \Delta g_{ij}(x), \quad (15)$$

all collinear singularities can be consistently factorized into the scale evolution of the bare photon and proton PDFs, depending on whether they originate from collinear configurations involving the initial-state photon or parton b . The required Born cross sections and LO $\Delta P_{ij}(x)$ are listed in the Appendix of Ref. [19], except for

$$\Delta P_{q\gamma} = C_A[2x - 1 - 2\varepsilon(1-x)]. \quad (16)$$

$C_A = 3$ in (16) and, below, $C_F = 4/3$ are the usual QCD color factors

The factorization scheme is fully specified by the choice of Δg_{ij} in (15) for which we take $\Delta g_{qq} = -4C_F(1-x)$, to guarantee helicity conservation within the HVBm prescription for γ_5 in d dimensions [28], and $\Delta g_{ij} = 0$ otherwise. The Euler constant γ_E and $\ln 4\pi$, both, like the scale μ , artifacts of dimensional regularization, are subtracted along with the $1/\varepsilon$ singularity. This defines the $\overline{\text{MS}}$ scheme in the polarized case, see, e.g., Ref. [29].

Finally, the last term in Eq. (6), $d\Delta\hat{\sigma}_{\gamma b}^{(f)}$, contains all the remaining, finite contributions, and the phase-space integration can be performed numerically in four dimensions. Monte Carlo integrations of (3) for different measurement functions \mathcal{S} can be done in parallel by randomly generating a sufficiently large sample of final-state configurations characterized by x_1, x_2, x, y, θ_1 , and θ_2 to account for the possibly large cancellations among the various terms. Remnants of the regularization of soft and collinear regions of phase are the mathematical distributions appearing in the different contributions to Eq. (6). Their proper definitions through a test function, properties, and numerical treatment are discussed at length in Refs. [25, 26, 19] and need not be repeated here.

3 Phenomenological Studies

3.1 Preliminaries

Based on our Monte Carlo code described above, we present a comprehensive study of charm quark photoproduction in longitudinally polarized muon-deuteron collisions at a c.m.s. energy of $\sqrt{S} \simeq 18$ GeV relevant for the COM-PASS experiment at CERN. Unless specified otherwise, we will show results for single-inclusive cross sections, differential in the transverse momentum p_T^D of the observed D meson.

The hadronization of the heavy quarks produced in the hard scattering is modeled using Eq. (4) with [30]

$$D^{Q \rightarrow H_Q}(z) = N_Q z^{\alpha_Q} (1-z). \quad (17)$$

The fragmentation function $D^{Q \rightarrow H_Q}$ is normalized such that its first moment is unity, i.e., $N_Q = (\alpha_Q + 1)(\alpha_Q + 2)$. For the remaining free parameter in (17) we take $\alpha_c = 5$ as the default value in all our calculations; see Table 4 in Ref. [31]. To estimate the uncertainties associated with the choice of α_c , we will vary it in the range $3 \leq \alpha_c \leq 7$ [31]. Like in the experimental analyses [15, 22, 23, 24], we adopt a cut $z > 0.2$ throughout our phenomenological studies, where z is the fraction of the energy of the photon taken by the D meson in the laboratory frame.

In the computation of the LO and NLO unpolarized cross sections we use the LO and NLO CTEQ6 parton densities [32] and values for the strong coupling α_s , respectively. In the polarized case, we adopt the best fit from the comprehensive global analysis performed by the DSSV group [2], which is the only set of helicity PDFs including constraints on $\Delta g(x, \mu_f^2)$ from pp data. The resulting PDFs are characterized by a small $\Delta g(x, \mu_f^2)$ in the x -range predominantly probed by RHIC experiments, $\int_{0.05}^{0.2} \Delta g(x, 10 \text{ GeV}^2) dx = 0.005^{+0.129}_{-0.164}$, with a node at $x \simeq 0.1$ [2]. To study the sensitivity of charm photoproduction data to different $\Delta g(x, \mu_f)$, we also use the GRVS “standard” set [33], which has a positive Δg that is larger in size than the one of DSSV. We note that the most recent RHIC data [7, 9] tend to prefer a polarized gluon density somewhere in between the ones obtained in the DSSV and GRVS fits [8, 9].

Equation (3) consistently includes both direct and resolved photon contributions to the spin-dependent photoproduction cross section by defining Δf_a^l as the convolution of the polarized lepton-to-photon splitting function $\Delta P_{\gamma l}$ and the structure functions Δf_a^γ of a circularly polarized photon, i.e.,

$$\Delta f_a^l(x_a, \mu_f) = \int_{x_a}^1 \frac{dy}{y} \Delta P_{\gamma l}(y) \Delta f_a^\gamma\left(x_\gamma = \frac{x_a}{y}, \mu_f\right). \quad (18)$$

Nothing is known experimentally about the Δf_a^γ , which account for the hadronic structure of a photon in the resolved case where $a \neq \gamma$ in (3). However, as will be demonstrated below, uncertainties associated with Δf_a^γ turn out to be negligible for charmed meson photoproduction at COMPASS kinematics. Contrary to inclusive hadron production [18], the resolved contribution turns out to be numerically small even when estimated with the “maximum” model for Δf_a^γ introduced in Ref. [34] and based on saturating the positivity limit $|\Delta f_a^\gamma(x, \mu_f)| \leq f_a^\gamma(x, \mu_f)$ at some low scale μ_f using the unpolarized set of GRV photon distributions [35] as reference. The direct part of the cross section (3) where $a = \gamma$ is obtained by setting

$$\Delta f_a^\gamma(x, \mu_f) = \delta(1-x). \quad (19)$$

in Eq. (18).

The collinear emission of a quasi-real photon with low virtuality Q and momentum fraction y off a muon with

mass m_μ is given by the Weizsäcker-Williams equivalent photon spectrum which reads in the polarized case [36]

$$\begin{aligned} \Delta P_{\gamma l}(y) = & \frac{\alpha}{2\pi} \left[\frac{1 - (1-y)^2}{y} \ln \frac{Q_{\max}^2(1-y)}{m_\mu^2 y^2} \right] \\ & + 2m_\mu^2 y^2 \left(\frac{1}{Q_{\max}^2} - \frac{1-y}{m_\mu^2 y^2} \right). \end{aligned} \quad (20)$$

The upper limit Q_{\max} is determined by experimental conditions. For COMPASS we take $Q_{\max}^2 = 0.5 \text{ GeV}^2$ and, in addition, restrict the fraction y of the muon’s momentum taken by the quasi-real photon to the range $0.1 \leq y \leq 0.9$.

We use $m_c = 1.35 \text{ GeV}$ as the value of the charm quark mass for all our results. For the factorization and renormalization scales in Eq. (3) we take $\mu_f = \mu_r = \xi(p_T^2 + m_c^2)^{1/2}$ with $\xi = 1$ as the central value and where p_T denotes the transverse momentum of the charm quark. As is commonly done, we vary them simultaneously in the range $1/2 \leq \xi \leq 2$ to estimate the residual scale dependence at NLO which represents the dominant source of theoretical uncertainty and can be taken as a rough measure of yet unknown higher order corrections.

3.2 Numerical Results

We begin our detailed numerical studies with a discussion of the scale dependence of the unpolarized and polarized photoproduction cross sections for D mesons in muon-deuteron collisions at COMPASS. Figure 2 shows the scale ambiguity from varying $\mu_{f,r} = \xi(p_T^2 + m_c^2)^{1/2}$ simultaneously in the range $1/2 \leq \xi \leq 2$ for the dominant direct photon contribution ($a = \gamma$) only. The solid lines denote our default choice of scales, $\xi = 1$. Since the published COMPASS data [15] are divided into three bins in the energy E_D of the produced D meson, $E_D < 30 \text{ GeV}$, $30 \leq E_D \leq 50 \text{ GeV}$, and $E_D > 50 \text{ GeV}$, we impose the cut $E_D < 30 \text{ GeV}$ in Fig. 2. Results for the other two bins in E_D are very similar and hence not shown.

As can be seen, the theoretical uncertainties due to the choice of scale are quite sizable, both in the unpolarized and in the polarized case and can be even further inflated by varying μ_f and μ_r independently as was done, for instance, in our study of heavy quark hadroproduction [19]. Also, possible variations of m_c , which we do not pursue here, would add to the theoretical error. By comparing the solid and dashed lines in Fig. 2 one can infer the relevance of the resolved photon cross section ($a \neq \gamma$). As was argued in Sec. 3.1, its contribution is rather small compared to the direct photon cross section and potential uncertainties due to the unknown Δf_a^γ do not matter.

Next, we study the role of the individual partonic subprocesses and their contribution to the photoproduction cross section in Eq. (3). Figure 3 displays the decomposition of the unpolarized direct photon cross section for $\xi = 1$, as shown in Fig. 2, in terms of the $\gamma\gamma$ and γq processes. Again, we choose $E_D < 30 \text{ GeV}$, and results for the other two bins in E_D are very similar. As expected, the photon-gluon fusion mechanism, which is already present

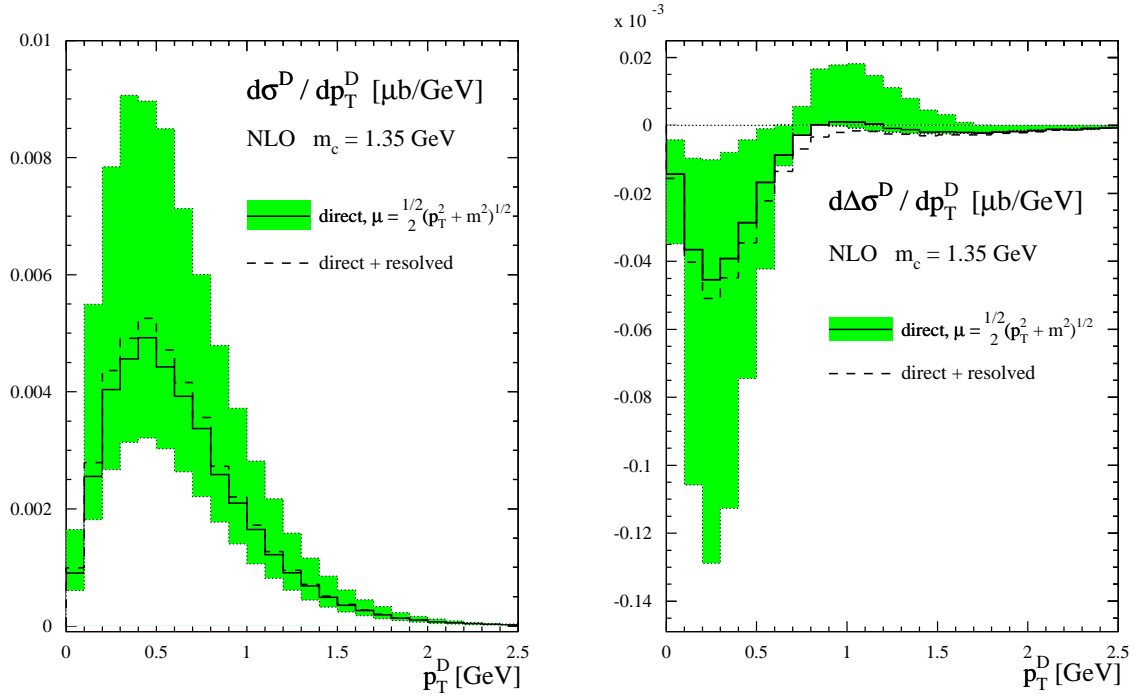


Fig. 2. Scale dependence of the single-inclusive transverse momentum spectrum of D mesons at NLO with $E_D < 30$ GeV for the dominant direct photon contribution in unpolarized (**left-hand side**) and polarized (**right-hand side**) muon-deutrium collisions at COMPASS kinematics; see text. Factorization and renormalization scales are varied simultaneously in the range $\mu = \xi(p_T^2 + m_c^2)^{1/2}$, $1/2 \leq \xi \leq 2$; the solid line refers to $\xi = 1$. In both panels, the dashed line shows the result for the sum of direct and resolved photon cross sections for $\xi = 1$.

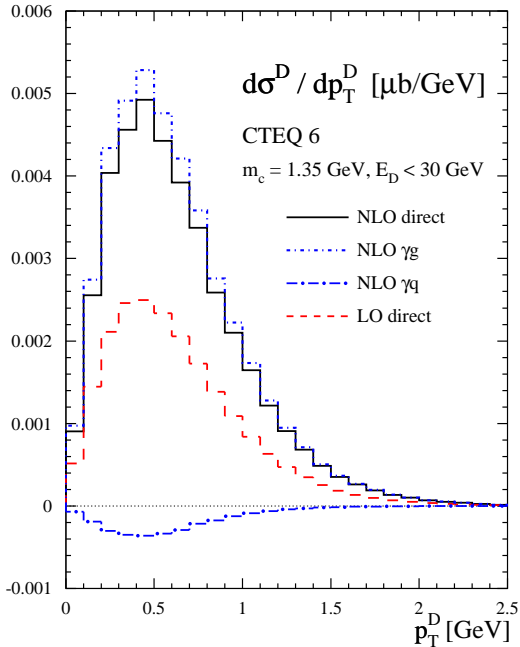


Fig. 3. Contributions of the individual γg and γq initiated subprocesses to the direct photoproduction cross section at NLO for $\xi = 1$ and $E_D < 30$ GeV (solid line). Also shown is the LO result (dashed line).

at LO, gives the main contribution to the cross section. The genuine NLO photon-quark channel yields a negative but small correction. The NLO result for the D meson production cross section is roughly a factor of two larger than the corresponding estimate at LO as can be gathered from comparing the dashed and solid lines in Fig. 3.

A similar exercise in the polarized case is shown in Fig. 4 for two different choices of helicity PDFs. First, one notices that the results obtained with the DSSV and GRSV sets differ in sign and magnitude of the cross section, which is readily explained by the very different gluon densities in both sets. The positive definite $\Delta g(x, \mu_f)$ of GRSV leads to a similar decomposition into γg and γq subprocesses as was observed in the unpolarized case in Fig. 3. Again, the cross section is strongly dominated by photon-gluon fusion, and the γq channel only yields a small correction. On the contrary, the oscillating $\Delta g(x, \mu_f)$ of the DSSV set of helicity PDFs leads to a negative $d\Delta\sigma^D$. Since the DSSV gluon is much smaller in size than the one of GRSV, the genuine NLO photon-quark contribution, which is numerically very similar in both PDF sets, is more important and yields more than a quarter of the cross section at small p_T^D . Another important observation concerns the relevance of NLO corrections which appears to be very different for the DSSV and GRSV helicity PDFs. This implies that higher order QCD effects do *not* cancel in the experimentally relevant double-spin

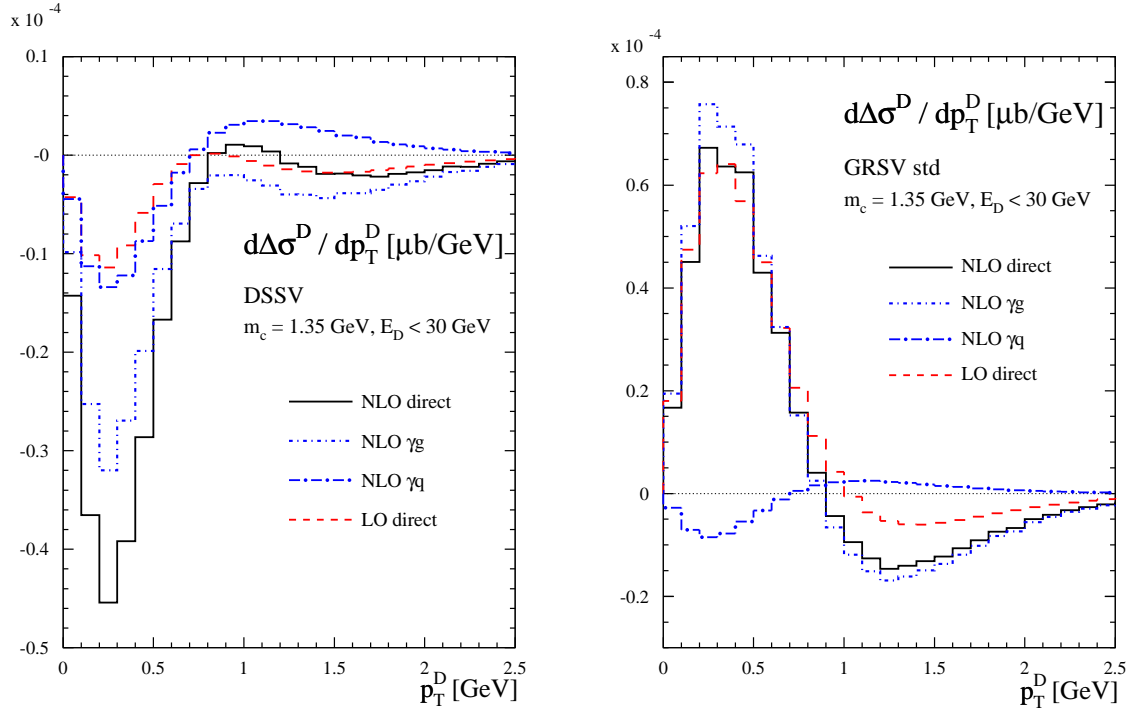


Fig. 4. As in Fig. 3 but now for the spin-dependent photoproduction cross section for two different choices of helicity PDFs: DSSV [2] (left-hand side) and GRSV “standard” [33] (right-hand side).

asymmetry,

$$A_{LL} \equiv \frac{d\Delta\sigma^D}{d\sigma^D}, \quad (21)$$

which we shall discuss in more detail below. Clearly, for a reliable quantitative analysis of charm photoproduction in terms of polarized PDFs, preferably as part of a global QCD fit, it is indispensable to properly include NLO corrections.

Figure 5 illustrates the uncertainties due to our choice of α_c in the fragmentation of the charm quark into the observed D meson. As in Fig. 2, we show the direct photon contribution for $\xi = 1$, but here we do not impose any cuts on the D meson to allow for a better comparability with the cross sections on the charm quark level which are presented as well. Compared to the factorization scale ambiguities, the dependence of our results on α_c is fairly moderate for both the unpolarized and the polarized cross sections. A similar observation was made in the case of hadroproduction [19]. Since charm quarks lose only very little of their momentum during hadronization, i.e., $D^{Q \rightarrow H_Q}(z)$ is peaked at fairly large values of z , the convolution (4) introduces only a rather small shift in the transverse momentum spectrum of the charm quarks. This can be inferred from the curves labeled $d(\Delta)\sigma/dp_T^c$ in Fig. 5.

Another interesting question concerns the range of momentum fractions x predominantly probed in the PDFs by the COMPASS data. Due to the dominance of the photon-gluon fusion process, charm photoproduction will mainly lead to a constraint on the gluon helicity distribution, which is the prime motivation for such measurements. The x distribution in LO and NLO, for both the unpolarized

and polarized direct photon contribution to the cross section (3) is explored in Fig. 6. No cuts are imposed in this calculation and the D meson spectrum is integrated over the entire phase space. As has to be expected from the fact that the PDFs enter the cross section (3) through a convolution, a broad range of x values is sampled. It turns out, however, that the mean value of x , where the distribution $d(\Delta)\sigma^D/dx$ is peaked, is fairly independent not only of the order in perturbation theory, LO or NLO, but to a large extent also of the chosen set of polarized or unpolarized PDFs. We roughly estimate the average momentum fraction to be $\langle x \rangle \simeq 0.08$ with an error of about $+0.12$ -0.03 .

Our results differ from preliminary estimates of $\langle x \rangle$ by the COMPASS collaboration [22, 23, 24], where NLO results have been obtained based on some parton shower Monte Carlo to approximate the phase space for the NLO matrix elements of Ref. [16]. Significant differences between $\langle x \rangle$ estimated in LO and NLO are found in this way. While their LO result for $\langle x \rangle$ agrees with our estimate of about 0.08, their preliminary NLO result is $\langle x \rangle = 0.28^{+0.19}_{-0.10}$. Since the details of the method are not yet published, it is not yet clear how these results can be compared to our full NLO calculation. We also note that once data on photoproduction processes are implemented in global QCD analyses of helicity PDFs, information on $\langle x \rangle$, though useful, is no longer required or relevant as the fits automatically impose the constraints from data for any given functional form assumed for the $\Delta f(x, \mu_f)$.

Next, we turn to the experimentally measured double-spin asymmetry, defined in Eq. (21), which was analyzed at LO accuracy and under certain simplifying assump-

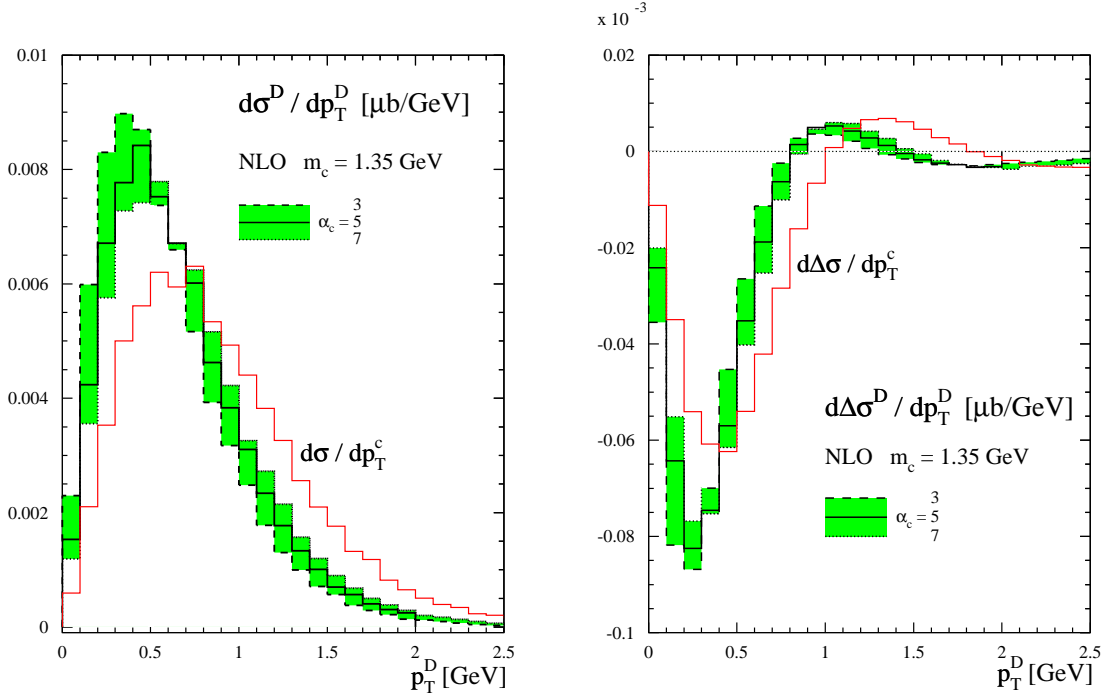


Fig. 5. As in Fig. 2, but now for variations of the parameter α_c in the fragmentation function (17) for the direct cross section computed with $\xi = 1$. No cuts on the D meson or charm quark are imposed; see text. Also shown are the results on the charm quark level, $d(\Delta)\sigma/dp_T^c$.

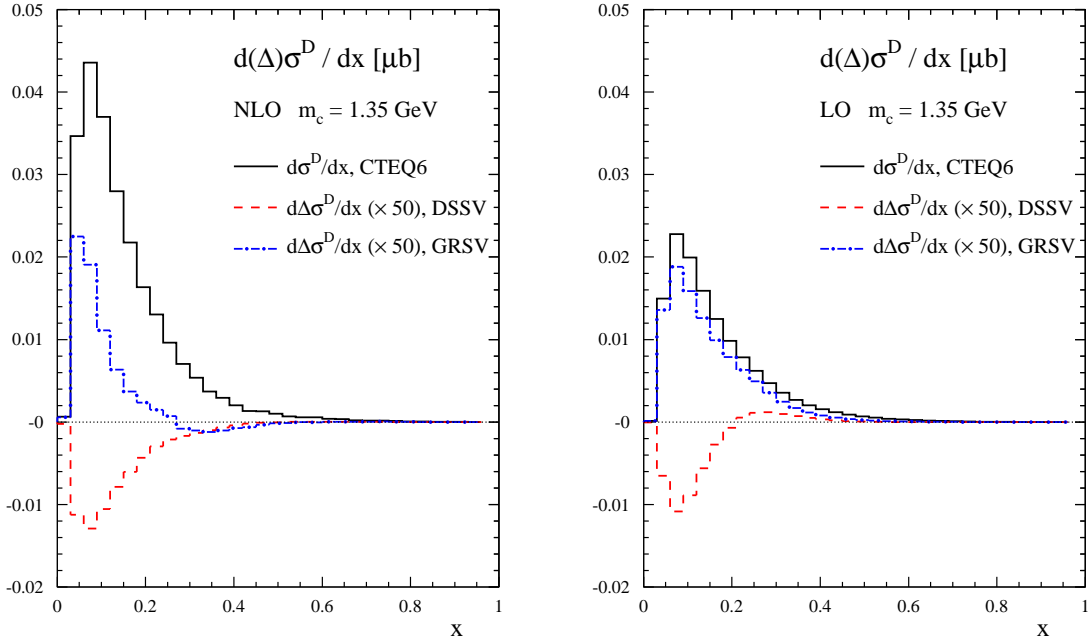


Fig. 6. Distribution $d(\Delta)\sigma^D/dx$ in the momentum fraction x probed in the PDFs at NLO (left-hand side) and LO (right-hand side) accuracy for both the unpolarized and polarized direct photon contribution, integrated over phase-space and without imposing cuts. Note that the polarized results are scaled by a factor of 50 for better visibility.

tions in terms of the mean gluon polarization $\Delta g(\langle x \rangle, \mu_f)/g(\langle x \rangle, \mu_f)$ by the COMPASS collaboration [15]; see the discussion below. Preliminary NLO estimates are also available at NLO with the hybrid method outlined above [22, 23, 24]. In Fig. 7 we show A_{LL} for the two sets of he-

licity PDFs used throughout this paper, by computing the ratio of the cross sections shown in Figs. 2 and 3 for $E_D < 30$ GeV. To resolve the differences in A_{LL} obtained with the DSSV and GRSV PDFs, which mainly stem from

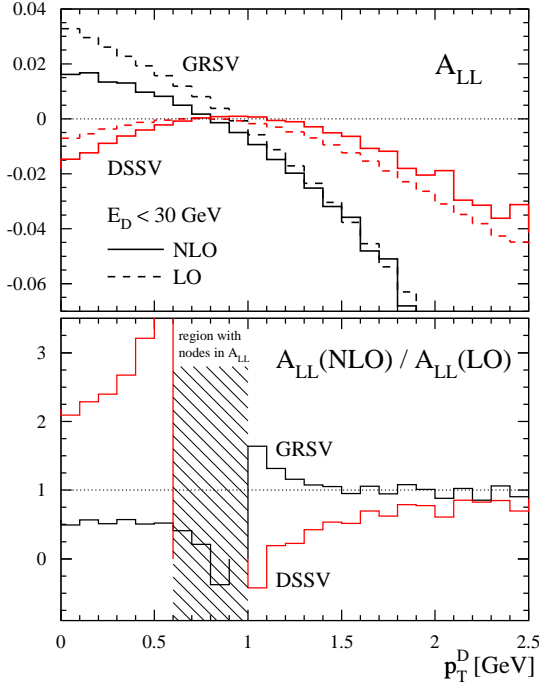


Fig. 7. Upper panel: double spin asymmetry in LO and NLO for D meson photoproduction at COMPASS kinematics for the DSSV and GRSV sets of helicity PDFs; as in Figs. 2 and 3 a cut $E_D < 30$ GeV is imposed; lower panel: the corresponding ratio of the NLO and LO results. The region where A_{LL} changes sign and the ratio becomes meaningless is indicated by the shaded band.

Δg , an experimental precision of at least $\delta A_{LL} \simeq 0.02$ needs to be achieved.

We also compare NLO and LO estimates of A_{LL} for both sets of helicity PDFs in the lower panel of Fig. 7 and find rather different patterns depending on p_T^D . At small p_T^D , the NLO A_{LL} is about a factor of two larger than the LO estimate for the DSSV set whereas a reduction by roughly the same amount is found with the GRSV PDFs. This illustrates that any approximations for the spin asymmetry, either to assume a cancellation of NLO corrections or a constant pattern independent of the choice of PDFs, are not justified and should not be used for analyzing data. Again, only a global analysis will lead to consistent results. Qualitatively very similar results have been obtained for other cuts on the energy E_D of the observed D meson, $30 \leq E_D \leq 50$ GeV and $E_D > 50$ GeV.

Finally, we compare our calculations at NLO accuracy with the available results from the COMPASS experiment. Figure 8 shows the data in three bins of the energy E_D of the detected D meson as a function of its transverse momentum p_T^D , imposing the cut $z > 0.2$. Note that instead of using the published data [15], we show new, preliminary results presented recently in Ref. [22, 23, 24]. A weighted average is performed to combine the results for the three decay channels $D \rightarrow K\pi$, $D \rightarrow K\pi\pi$, and $D \rightarrow K\pi\pi\pi$ listed in [22, 23, 24]. We adopt the photon

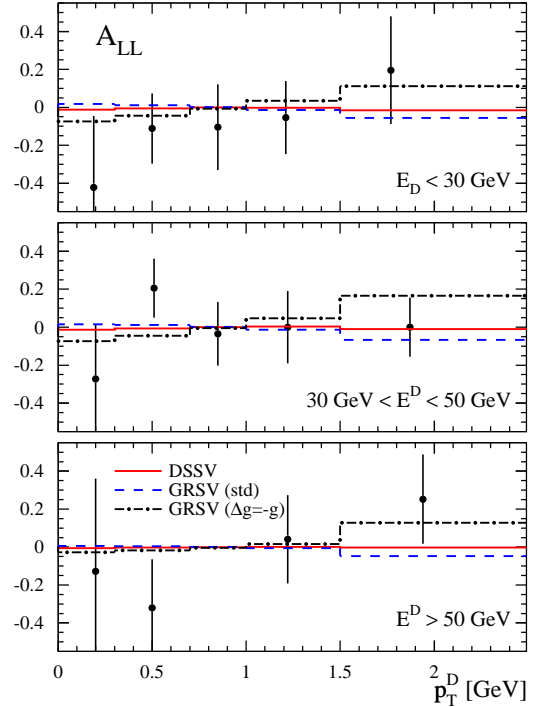


Fig. 8. Predictions for the double-spin asymmetry for D meson photoproduction at COMPASS at NLO accuracy for three different sets of helicity PDFs and in three bins of E_D compared to data. Note that in the bottom panel one of the data points is outside the range shown for A_{LL} .

polarization dilution factors tabulated in Ref. [22, 23, 24] to convert the data for A_{LL} given in the photon-nucleon system to the double-spin asymmetries for muon-nucleon scattering computed with our Monte Carlo code.

Clearly, present experimental uncertainties are too large to discriminate between different spin-dependent gluon densities. Apart from the DSSV and GRSV “standard” sets, we also use an extreme GRSV set, characterized by a very large and negative gluon density based on setting $\Delta g(x, \mu_0) = -g(x, \mu_0)$ at some low bound-state like input scale μ_0 [33] for the evolution. Despite leading to a distinctively different A_{LL} than our two default sets, all results are compatible with data within the experimental precision.

To overcome the statistical limitations, fewer bins have to be used or all data need to be combined. COMPASS has performed such an analysis [15] yielding the result for the gluon polarization quoted in Fig. 1, which is compatible with similar extractions of $\Delta g/g$ from hadron production data. These kind of analyses are LO estimates, assuming, in addition, that the convolutions of the PDFs with the partonic hard cross sections in Eq. (3) can be approximated as

$$A_{LL} = \frac{\Delta g \otimes d\Delta\hat{\sigma}_{\gamma g}}{g \otimes d\Delta\hat{\sigma}_{\gamma g}} \approx \frac{\Delta g}{g} \left\langle \frac{d\Delta\hat{\sigma}_{\gamma g}}{d\hat{\sigma}_{\gamma g}} \right\rangle. \quad (22)$$

Here, the “analyzing power” $\langle \frac{d\Delta\hat{\sigma}_{\gamma q}}{d\hat{\sigma}_{\gamma q}} \rangle$ is evaluated at some average kinematics. As mentioned before, in a proper global analysis of helicity PDFs one does not need to resort to any of these approximations whose validity is difficult to estimate or justify. With our new Monte Carlo program it is now possible to perform such an analysis at NLO accuracy in the future. As we have demonstrated in some detail, NLO corrections are indispensable for a quantitative analysis. Most importantly, they do not cancel in the spin asymmetry as one might naively expect.

Apart from the phenomenological applications presented here, our code can be also used to estimate spin asymmetries for charm and bottom photoproduction and their impact on our knowledge of the spin structure of the nucleon at higher c.m.s. energies intended for a first polarized lepton-ion collider. Details on the EIC project can be found in [10]. Such a machine will be indispensable to finally unravel the quark and gluon contributions to the nucleon spin [11].

4 Summary and Outlook

We have presented a flexible parton-level Monte Carlo program to compute heavy flavor distributions at NLO accuracy in longitudinally polarized lepton-nucleon collisions in the photoproduction regime. For the first time, we consistently include both direct and resolved photon contributions and found the latter to be negligibly small for charm production at COMPASS kinematics. Experimental acceptance cuts, the hadronization of the produced heavy quark pair, and, if needed, their subsequent semi-leptonic decays can be included in phenomenological applications.

Heavy flavor photoproduction receives its importance for the field of spin physics from its expected strong sensitivity to the polarized gluon density which we confirm. In general, higher order corrections are found to be sizable and strongly dependent on the chosen set of helicity PDFs. This is also true for the experimentally relevant spin asymmetry despite naive expectations that QCD corrections cancel in the ratio. Theoretical uncertainties due to the choice of the factorization scale are sizable even at next-to-leading order accuracy while ambiguities from the exact form of the charm quark fragmentation function are less important.

The results obtained in this paper allow one to include data on charm photoproduction consistently into future global analyses of helicity PDFs. We have shown that data from COMPASS can lead in principle to a constraint on the polarized gluon density at a momentum fraction of about 0.1. Currently available data will have, however, very little impact on existing fits due to the size of the experimental uncertainties which are too large to discriminate between different gluon densities.

In addition to the phenomenological studies performed in this paper, our code will be useful in assessing the physics impact of heavy quark photoproduction at a possible future polarized lepton-ion collider like the EIC project.

Note Added

While completing our analysis, the preliminary COMPASS results [22,23,24] discussed in this paper have been published in [37]. Our conclusions remain unchanged.

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